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LCA FOR ENERGY SYSTEMS AND FOOD PRODUCTS

# Environmental life cycle assessment for rapeseed-derived biodiesel

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**Abstract**
*Purpose* Biofuels have received special research interest, driven by concerns over high fuel prices, security of energy supplies, global climate change as well as the search of opportunities for rural economic development. This work examines the production of biodiesel derived from the transesterification of crude rapeseed oil, one of the most important sources of biodiesel in Europe, paying special attention to the environmental profile-associated to the manufacture life cycle (i.e., cradle-to-gate perspective).
*Methods* To do so, a Spanish company with an average annual biodiesel production of 300,000 t was assessed in detail. The Life Cycle Assessment (LCA) study covers the whole life cycle, from the production of the crude rapeseed oil to the biodiesel production and storage. The inventory data for the foreground system consisted of average annual data obtained by on-site measurements in the company, and background data were taken from databases. Seven impact categories have been assessed in detail: abiotic depletion, acidification, eutrophication, global warming, ozone layer depletion, land competition, and photochemical oxidant formation. An energy analysis was carried out based on the cumulative nonrenewable fossil and nuclear energy demand as an additional impact category. Furthermore, well-to-wheels environmental characterization results were estimated and compared per ton-kilometer for the biodiesel (B100) and the conventional diesel so as to point out the environmental drawbacks and strengths of using biodiesel as transport fuel in a 28 t lorry.
*Results and discussion* The results showed that the cultivation of the rapeseed was the main key issue in environmental terms (68 %–100 % depending on the category) mainly because of fertilizer doses and intensive agricultural practices required. With regard to the biorefinery production process, pretreatment and transesterification sections considerably contribute to the environmental profile mostly due to electricity and chemical requirements. Concerning the well-to-wheels comparison, using B100 derived from rapeseed oil instead of petroleum-based diesel would reduce nonrenewable energy dependence (−20 %), GHG emissions (−74 %), and ozone layer depletion (−44 %) but would increase acidification (+59 %), eutrophication (+214 %), photochemical smog (+119 %), and land competition.
*Conclusions* The information presented in this study could help to promote the use of renewable transport biofuels. However, the extensive implementation of biodiesel (particularly rapeseed oil-derived biodiesel) in our society is enormously complex with many issues involved not only from environmental but also economical and social points of view.

**Keywords** B100 · Biofuel · *Brassica napus* L. · Diesel · Edible crop · Environmental analysis · LCA · Life cycle inventory (LCI)

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## 1 Introduction

Environmental issues, growing demand for energy, political concerns, and medium-term depletion of petroleum have created the need for development of sustainable technologies based on renewable raw materials (Dale 2008; Goldemberg 2008). The search for alternative fuels is persistently under way with 90 % of transport fuels being hydrocarbon sourced and uncertainty around depletion levels of conventional oil reserves mounting.

Nowadays, there is a general scientific consensus that observed trends in global warming have been caused by fossil fuel combustion and anthropogenic emissions of greenhouse gases (GHG) including nitrous oxide ($N_2O$), carbon dioxide ($CO_2$), and methane ($CH_4$). Alternative renewable raw material-based fuels are, therefore, of growing interest and represent an alternative (Sander and Murthy 2010; Yan et al. 2010). Since biofuels might help to meet the future energy supply demands, they could offer a new agricultural product for stimulating rural economies as well as they could contribute to a reduction of GHG emissions.

Nowadays, two different types of biofuels are being used in considerable amounts all over the world: bioethanol and biodiesel. Bioethanol is produced in large amounts from maize in the USA, sugarcane in Brazil, and in smaller amounts from sugar beet and wheat in Europe (Goldemberg 2008). Biodiesel is produced predominantly from rapeseed in Europe, palm oil in Asia, and soybeans in Brazil (Goldemberg 2008), and it is commonly used in the form of B20 (20 % biodiesel and 80 % diesel blend by volume) as well as Fischer–Tropsch diesel (synthetic) in its pure form (B100) in normal diesel vehicles (Yan et al. 2010). The biodiesel blend commercialization depends on country-specific legislation: the use of B100 is common in Germany, blends up to B20 and B100 are available in Portugal, and B30 is normally used in France (Mata et al. 2011). All of them are derived from agricultural crops and are called as first-generation (1 G) biofuels. However, there is special interest on the production of later generation biofuels from a variety of lignocellulosic biomass sources, commonly known as second-generation feedstocks, as well as from algal cultures using advanced technological processes (Luque et al. 2010; González-García et al. 2011). They are known as second-generation (2 G) and third-generation (3 G) biofuels, respectively (Sander and Murthy 2010). However, not everyone is excited about biofuels, since numerous concerns exist about environmental (pollution, land, and water use) and social impacts (food and feed availability, prices) (Luque et al. 2010). Therefore, biofuel production and use is a very complex issue involving more than agricultural and chemical engineering, and a good perspective of biofuels should include a multidisciplinary approach (Luque et al. 2010).

Rapeseed (*Brassica napus* L.) is an edible crop which drives too many concerns related to social impacts, especially in developing countries. This is the case of the “food for fuel” debate as biofuels could replace food crops leading to considerable food price increments as well as it should cause biodiesel cost increase (Luque et al. 2010; Mata et al. 2011). For this reason, currently, special attention is being focused on the use of cooking oils, animal oils, nonedible oils from feedstocks (*Jatropha curcas* L., *Brassica carinata* L., …) as well as oils derived from algae (Sander and Murthy 2010). However, rapeseed was considered as a case study in this paper for several reasons: (i) the importance of this crop for the European biodiesel production, e.g., in Spain (Lechón et al. 2007; Stromberg et al. 2010); (ii) this crop is an ideal raw material with regard to combustion characteristics, oxidative stability, and cold temperature behavior in producing biodiesel; (iii) this crop is well known to farmers; (iv) this crop presents a stable range of production; and (v) this is the main raw material used in the Spanish biodiesel plant under assessment.

Biodiesel is a biodegradable and nontoxic diesel fuel substitute which has a remarkable added value over petroleum-based diesel (Luque et al. 2010). Important benefits are associated to biodiesel use instead of petroleum-based diesel such as: (i) health benefits (less carcinogenic emissions—up to 94 %), (ii) environmental benefits (lower pollution rates and higher degradability—up to four times), and (iii) mechanical/economical benefits (higher lubricity which involves longer engine life, reduction of maintenance costs, and higher fuel economy) (Luque et al. 2010).

Life Cycle Assessment (LCA) is a standardized methodology for addressing all the environmental concerns which arise from biodiesel production by evaluating the potential environmental impacts of product systems over their whole life cycle chain (ISO 14040 2006). LCA has widely been applied for the evaluation of the environmental performance of biofuel products, in particular for 1 G (Panichelli et al. 2009; Singh et al. 2010; Mata et al. 2011), 2 G (González-García et al. 2009a; 2009b; 2010a; 2010b; 2010c; 2011; Talens Peiró et al. 2010), and 3 G biofuels (Sander and Murthy 2010; Mata et al. 2011). Specifically for biodiesel, it has been the aim of LCA studies considering different raw materials for its production: cooking oil (Talens Peiró et al. 2010), rapeseed oil (Canola Council of Canada, 2010; Talens Peiró et al. 2010; Mata et al. 2011), soybean oil (Panichelli et al. 2009; Mata et al. 2011), palm oil (Mata et al. 2011), jatropha oil (Mata et al. 2011), sunflower oil (Mata et al. 2011) as well as algae (Sander and Murthy 2010; Mata et al. 2011: Shirvani et al. 2011).

Concerning rapeseed oil-derived biodiesel, only Talens Peiró et al. (2010) presents a summary of energy-based inputs

and outputs for the production of biodiesel. Therefore, to the best of our knowledge, this paper present for the first time a detailed life cycle inventory (LCI) and related impacts of biodiesel production from an edible vegetable oil extracted from rapeseed based on an acid pretreatment stage and a methanol-based transesterification.

## 2 Goal and scope definition

### 2.1 Objectives

The primary aim of this study was to analyze the environmental impacts and energy balance of the production of biodiesel from rapeseed oil from an environmental point of view in a specific Spanish plant to identify the environmental hot spots of the transformation process in order to propose improvement options, where future alternatives could be focused on. A secondary goal was also to provide information on possible drawbacks and advantages associated with the use of biodiesel instead of petroleum-based diesel in a conventional 28 t truck, based on a well-to-wheel comparison of the two options using available data from the literature.

To do so, a Spanish company located in Ferrol (NW Spain), considered representative of the state-of-art due to its high biodiesel production volume and high efficiency equipment, was selected for detailed assessment. There, different crude oils are processed (soybean, rapeseed, and palm oils) depending on the availability and market prices. However, it has only been paid attention on rapeseed oil because its average annual biodiesel production is 300,000 t, the largest.

### 2.2 Functional unit

The selection of the functional unit is really important, since it has an important influence on the results (González-García et al. 2009a, 2009b; Singh et al. 2010) and its choice depends on the aim of study. As mentioned, the main function of this study is the production of biodiesel from rapeseed (*B. napus* L.) by means of the transesterification of the edible oil, and therefore, a functional unit of 1 t of biodiesel was considered (González-García et al. 2009a; Talens Peiró et al. 2010) with the following technical specifications: content of 237 mg/kg, average density (15°C, vacuum) of 876.9 kg/m$^3$, kinetic viscosity (40°C) of 4.39 mm$^2$/s, and maximum sulfur content of 10 ppm. For the second goal defined and following the recommendations of Singh et al. (2010), the functional unit considered was 1 t km (i.e., the transport in a 28-t truck of 1 t of a good for a distance of 1 km).

### 2.3 Description of the system under study

The production of biodiesel is based on different technologies of conversion and requires high quality raw materials and a high content of triglycerides. Biodiesel is conventionally produced via triglyceride transesterification from vegetable oils (also, waste oils and animal fats) with short-chain alcohols (e.g., methanol) to yield fatty acid methyl esters (FAME) (which are the biodiesel itself) and glycerol as a by-product. The conversion methods can be classified as chemical catalytic (base or acid catalysis), biocatalytic (enzyme catalysis), and noncatalytic processes (Luque et al. 2010). The catalytic processes can be homogeneously catalyzed employing NaOH and KOH as homogenous catalyst. This production process presents several drawbacks based on high sensitivity to water and free fatty acids in the feedstocks, which restrict the use to dehydrated and low acidic vegetable oils. Another chemical process is heterogeneously catalyzed where solid acid (e.g., alkali metal and alkaline earth metal carbonates and oxides, basic ion-exchange resins) and base catalysts are employed as heterogeneous catalyst. This process is favorable because the catalyst can be recycled many times and the process is cleaner and simpler. The biocatalytic process is based on the use of enzymes (e.g., lipases) in triglyceride transesterifications. It is an expensive production process, and up to date, it is based on laboratory studies. Finally, the noncatalyzed processes are based on the use of supercritical alcohol (e.g., methanol) for simultaneously transesterification of triglycerides and esterification of fatty acids. This production process is very effective, with high FAME yield in a short reaction time, but it is really expensive due to the supercritical conditions (Luque et al. 2010).

In this study, we have considered a conventional transesterification process of well-known industrial use. In this process, crude rapeseed oil (mainly composed of triglycerides) is converted to FAME or biodiesel using an alcohol (in this case, methanol, the most common) as reagent in the presence of sodium methylate as catalyst.

The system process was divided in two main subsystems (Fig. 1):

1. SS1: rapeseed oil production, which includes the agricultural production of the rapeseed and extraction of crude oil from the seeds.
2. SS2: biodiesel production, which includes all the activities which take place in the biorefinery. So, this subsystem was divided into seven sections which will be detailed next:
   (a) SS2.1—storage tanks of chemicals, product, and coproducts: This section includes the maintenance and operation of the different tanks required in the biorefinery throughout the biodiesel production

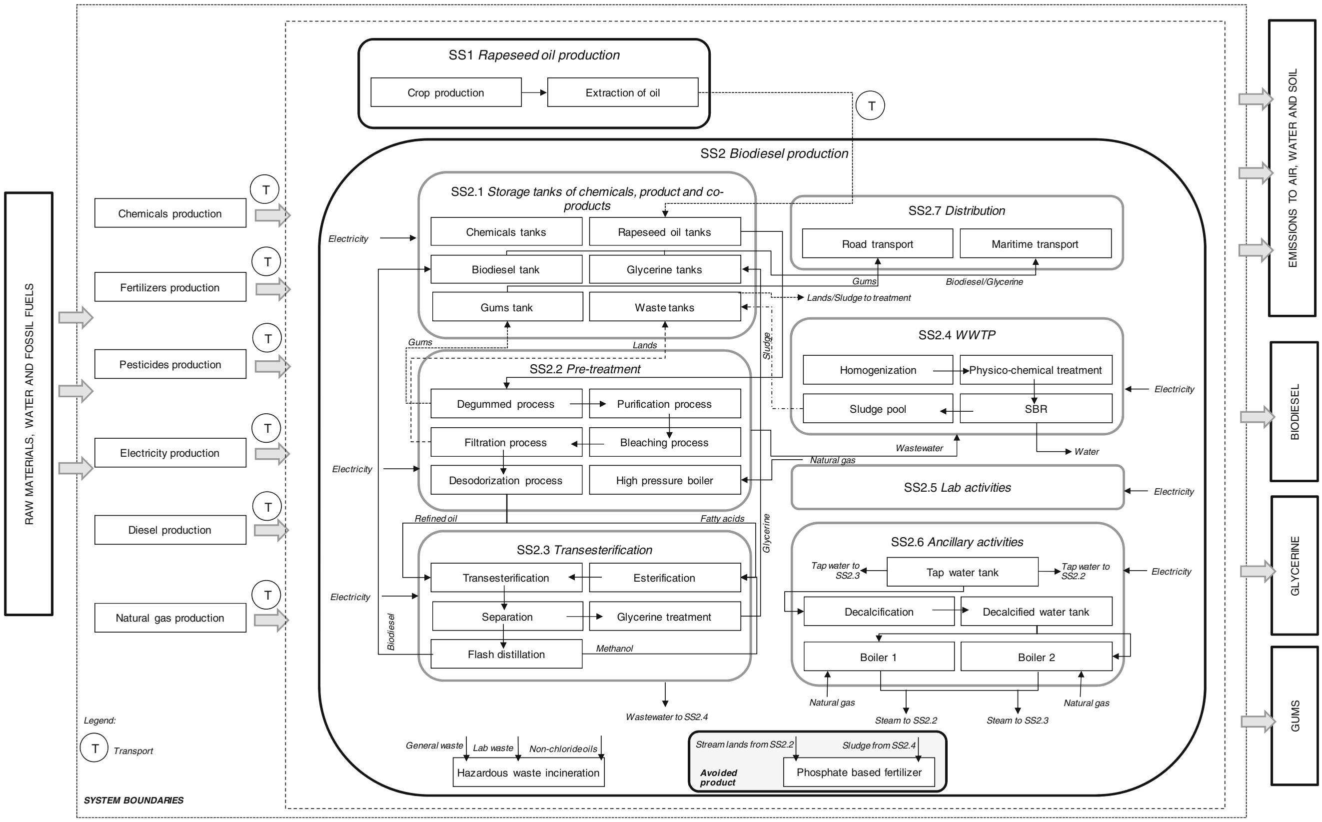


**Fig. 1** System boundaries and process chain of the rapeseed oil-derived biodiesel production process (cradle-to-gate perspective)

process. Each tank has associated a specific pump and they have to be inerted with nitrogen before being filled.

(b) SS2.2—pretreatment: The first step in the biodiesel production process is the extraction of impurities such as phosphatides, free fatty acids, and tocopherols which are not desirable and can stop the reactions. The phosphates are extracted ("degummed process") with phosphoric acid by means of gum formation in an agitated reactor at high temperature. Afterwards, the mixture is sent to a mixer where a part of the fatty acids are saponified with caustic soda. Subsequently, citric acid and silica gel are added in order to eliminate possible remaining phospholipids and metals ("purification process"), which constitute a waste stream known as "lands." Next, it is sent to a mixer where bentonite is added to bleach the stream ("bleaching process") and filtered. Finally, the filtered oil is heated at high temperature ("desodorization process") in order to separate the fatty acids and refined oil, which will be destined to transesterification, and later, the cooled stream is stored in the corresponding tank. The high temperature required in this process involves the requirement of a high pressure boiler where natural gas and deionized water are used.

(c) SS2.3—transesterification: The transesterification reaction is carried out in three continuous mixed serial reactors, working at 60°C and atmosphere pressure. The refined oil is mixed with methanol and potassium methylate (catalyst). For the stoichiometric transesterification reaction, 4 mol of alcohol are used per mole of triglyceride, which results in 4 mol of FAME (biodiesel) and 1 mol of glycerine. However, the theoretical methanol to triglyceride molar ratio is 3:1, but it is commonly used in excess of alcohol to complete the reaction and increase the yield. From the reactions, glycerine is obtained and separated from the bottoms of the reactors to be treated later. The final output stream from the third reactor contains the biodiesel, surplus methanol, and glycerine, and it is sent to the methylester purification process. The methanol is separated

from the remaining stream (previously heated) by atmospheric flash distillation and recycled to the system. The remaining stream is decanted to separate the biodiesel from the glycerine, which is sent to the glycerine treatment step. The biodiesel, with traces of soaps, glycerine, and catalyst, is washed with water and citric acid, and then separated and sent to the dried step for storage. The glycerine is treated to be purified and mixed with chlorhydric acid in a first step and with caustic soda in a second one. Fatty acids, separated in the desodorization process together with others from the distillation column of methanol (see Fig. 1), are esterified, where the fatty acids contained in the recovered oils are neutralized. This reaction is carried out in a continuous reactor at 110°C and 7 atm with addition of methanol and sulfuric acid as catalyst.

(d) SS2.4—wastewater treatment plant (WWTP): Wastewater from the biodiesel production process is treated on-site by means of a homogenization pool, a physicochemical flotation treatment, a sequential batch reactor, a sludge pool, and finally, a final dumping pool, where water is decanted for 2 h. Treated water is discharged into the sea and decanted sludge is centrifuged, dried, and stored for further management. The treated wastewater is from an industrial origin (mainly from the pretreatment and transesterification sections), so it presents high oil, fat, and suspended solid contents which hardly settle.

(e) SS2.5—laboratory activities: In this section, samples from different points of the process are analyzed in order to identify the characteristics of the different streams and check the quality of raw materials and products. Electricity and main chemicals used in this section were quantified and included in the assessment.

(f) SS2.6—ancillary activities: This section involves steam production as well as tap water requirement in each process. Concerning steam production, water is firstly decalcified with sodium chloride before sending to the boilers where natural gas is used for combustion. Once the steam is produced, it is sent to the corresponding units and it returns to the tank as hot water, part of this water being recycled and the other used in other sections of the plant.

(g) SS2.7—distribution: This final stage includes the distribution of the main product and coproducts (i.e., glycerine and gums) to their final destinations by means of different transport modes (maritime and road), and they were specified in Table 1.

**Table 1** Average distances and transport mode considered for the inputs to the biorefinery

| Material | Transport mode | Distance (km) |
|---|---|---|
| Inputs to the biorefinery | | |
| Rapeseed oil | Ship | 5,050 |
| Methanol | Ship | 7,200 |
| Silica gel | Truck | 2,328 |
| Potassium methylate | Truck | 2,328 |
| Citric acid | Truck | 1,121 |
| Phosphoric acid | Truck | 1,121 |
| Bentonite | Truck | 688 |
| Solvents, absorbents | Truck | 440 |
| Filtration materials | Truck | 440 |
| Nonchloride oils | Truck | 440 |
| Sulfuric acid | Truck | 289 |
| Nitrogen | Truck | 289 |
| Chlorhydric acid | Truck | 154 |
| Sodium hydroxide | Truck | 154 |
| Sludge from WWTP | Truck | 120 |
| Plastic and glass wastes | Truck | 120 |
| Sodium chloride | Truck | 54 |
| Lab wastes | Truck | 54 |
| Lands from pretreatment | Truck | 41 |
| Natural gas | Truck | 14 |
| Product and coproducts | | |
| Biodiesel | Ship | 14.0 |
| Glycerine | Ship | 2,078 |
| Gums | Truck | 18.5 |

## 3 Life cycle inventory (LCI)

### 3.1 Inventory analysis, data quality, and simplifications

High quality data is essential to make a reliable evaluation in a LCA analysis, and this step requires a lot of time and effort. The LCI data for the foreground system consisted of average annual data obtained by on-site measurements in the company (Table 2) by means of an industrial control system, supervisory control and data acquisition (SCADA). As it was mentioned before, different crude oils can be processed in the plant.

The information regarding the manufacture of the main raw material (the rapeseed oil) and other background systems (such as natural gas, chemicals, electricity, and packaging materials production processes) were obtained from databases (Table 3). Specifically, rapeseed

**Table 2** Global average inventory for the rapeseed-derived biodiesel production

| Inputs from technosphere | | | |
|---|---|---|---|
| Materials | | Energy | |
| SS2.1 | | Electricity (SS2.1) | 50 kWh |
| Nitrogen | 0.77 kg | Electricity (SS2.2) | 195 kWh |
| SS2.2 | | Electricity (SS2.3) | 100 kWh |
| Rapeseed oil (from SS1) | 1.02 t | Electricity (SS2.4) | 47 kWh |
| Sodium hydroxide | 1.91 kg | Electricity (SS2.5) | 0.40 kWh |
| Phosphoric acid | 1.01 kg | Electricity (SS2.6) | 80 kWh |
| Bentonite | 0.80 kg | | |
| Citric acid | 0.42 kg | Transport | |
| Silica gel | 2.50 kg | Truck 16–32 t (SS2.1) | 222.5 kg km |
| Steam (from SS2.6) | 194.7 kg | Truck 16–32 t (SS2.2) | 8.16 t km |
| Natural gas | 0.58 kg | Truck 16–32 t (SS2.3) | 41.66 t km |
| Tap water | 160.7 kg | Truck 16–32 t (SS2.4) | 315.0 kg km |
| Deionized water | 8.30 g | Truck 16–32 t (SS2.5) | 102.3 kg km |
| SS2.3 | | Truck 16–32 t (SS2.6) | 75.07 kg km |
| Methanol | 98.3 kg | Truck 16–32 t (SS2.7) | 18.48 t km |
| Sulfuric acid | 0.30 kg | Transoceanic tanker (SS2.2) | 5,151 t km |
| Chlorhydric acid | 13.24 kg | Transoceanic tanker (SS2.3) | 707.8 t km |
| Sodium hydroxide | 1.79 kg | Transoceanic tanker (SS2.7) | 2,077.5 t km |
| Nitrogen | 0.23 kg | Transoceanic freight ship (SS2.7) | 14.0 t km |
| Tap water | 20 kg | | |
| Steam (from SS2.6) | 129.82 kg | | |
| Potassium methylate | 16.7 kg | | |
| Citric acid | 0.28 kg | | |
| SS2.4 | | | |
| Ureum | 0.23 kg | | |
| Sodium hydroxide | 0.56 kg | | |
| Coagulant | 0.56 kg | | |
| SS2.5 | | | |
| Acetone cyanohydrin | 0.01 kg | | |
| Helium | 0.047 kg | | |
| Heptane | 0.01 kg | | |
| Ultrapure water | 0.008 kg | | |
| Packaging materials | 0.122 kg | | |
| SS2.6 | | | |
| Tap water | 319.29 kg | | |
| Sodium chloride | 0.037 kg | | |
| Natural gas | 5.22 kg | | |
| Outputs to technosphere | | | |
| Product | | Waste to treatment | |
| Biodiesel | 1 t | Lands (from SS2.2) | 3.30 kg |
| Coproducts | | Sludge (from SS2.4) | 1.55 kg |
| Glycerine | 110 kg | Waste to incineration (from SS2.5) | 0.292 kg |
| Gums | 20 kg | | |
| Outputs to environment | | | |
| Air emissions | | Water emissions | |
| Nitrogen (SS2.1) | 0.77 kg | Suspended solids | 1.72 g |
| Carbon dioxide (SS2.2) | 13.17 kg | Ammonia | 2.18 g |
| Oxygen (SS2.2) | 12.05 kg | Chemical oxygen demand | 15.78 g |

**Table 2** (continued)

| Inputs from technosphere | | | |
|---|---|---|---|
| Sulfur dioxide (SS2.2) | 0.006 kg | Phosphorous | 0.033 g |
| Carbon monoxide (SS2.2) | 0.006 kg | | |
| Nitrogen oxides (SS2.2) | 0.006 kg | | |
| Carbon dioxide (SS2.6) | 32.27 kg | | |
| Oxygen (SS2.6) | 19.49 kg | | |
| Sulfur dioxide (SS2.6) | 0.015 kg | | |
| Nitrogen oxides (SS2.6) | 0.014 kg | | |
| Carbon monoxide (SS2.6) | 0.009 kg | | |

oil production was taken from Ecoinvent database (Jungbluth et al. 2007), since the production process in Canada is similar to the system described there.

Concerning waste generation, the stream lands (SS2.2), rich in phosphorous and metals, is treated with lime to be further used as fertilizer. Sludge (SS2.4) has also a fertilizer value and is used for land application. So, both were treated as avoided products because they are currently used as substitute for a phosphate-based fertilizer.

Lab wastes, solvents, absorbents, filtration materials, nonchloride oils as well as plastic and glass based wastes

**Table 3** Summary of data sources

| Energy | Electricity (Spanish electricity profile) | Ecoinvent database (Dones et al. 2007) |
|---|---|---|
| Chemicals | Rapeseed oil | Ecoinvent database (Jungbluth et al. 2007) |
| | Sodium hydroxide | Ecoinvent database (Althaus et al. 2007) |
| | Phosphoric acid | Ecoinvent database (Althaus et al. 2007) |
| | Bentonite | Ecoinvent database (Kellenberger et al. 2007) |
| | Citric acid[a] | BREW Project (2006) |
| | Silica gel | IDEMAT database (2001) |
| | Tap water | Ecoinvent database (Althaus et al. 2007) |
| | Deionized water | Ecoinvent database (Althaus et al. 2007) |
| | Ureum | ETH-ESU 96 database (2004) |
| | Methanol | Ecoinvent database (Althaus et al. 2007) |
| | Sulfuric acid | Ecoinvent database (Althaus et al. 2007) |
| | Chlorhydric acid | Ecoinvent database (Althaus et al. 2007) |
| | Potassium methylate[b] | Field data and Ecoinvent database (Althaus et al. 2007) |
| | Coagulant[c] | Algra (2002) |
| | Acetone cyanohydrin | Ecoinvent database (Althaus et al. 2007) |
| | Helium | Ecoinvent database (Althaus et al. 2007) |
| | Heptane | Ecoinvent database (Althaus et al. 2007) |
| | Sodium chloride | Ecoinvent database (Althaus et al. 2007) |
| | Ultrapure water | Ecoinvent database (Althaus et al. 2007) |
| | White packaging glass | Ecoinvent database (Hischier et al. 2009) |
| Transport | Trucks 16–32 t | Ecoinvent database (Spielmann et al. 2007) |
| | Transoceanic tankers/freight ship | Ecoinvent database (Spielmann et al. 2007) |
| Waste treatment | Hazardous waste incineration | Ecoinvent database (Doka 2007) |
| Avoided product | Phosphate-based fertilizer | Ecoinvent database (Nemecek and Käggi 2007) |

[a] Only energy use and GHG emission association are taken into account due to lack of information

[b] Potassium methylate is a common catalyst based on 98 % methanol with elemental potassium. Therefore, we have considered its production from methanol and potassium hydroxide due to the lack of information

[c] It was considered aluminium polychloride. Due to the lack of information, we only managed chemical consumption such as deionized water, hydrochloric acid, and aluminium hydroxide

have been quantified together as hazardous waste and assumed to be incinerated. Regarding biodiesel and coproduct distribution, different transport modes (maritime and road) were considered in this study, and they were previously specified in Table 1.

### 3.2 Allocation procedure

In this study, not only is biodiesel produced (main product) but glycerine and gums are also obtained. Among the different possible procedures, an economic allocation was selected in this study for several reasons: (i) large differences in the market prices for the different products and (ii) biodiesel is the driving force of the company under assessment. Therefore, allocation was based on the annual sales on the company (confidential data), the factors being directly supplied by the company as follows: 98 % for biodiesel, 1.45 % for glycerine, and 0.55 % for gums.

## 4 Life cycle assessment study for the rapeseed oil-derived biodiesel

Among the steps defined within the life cycle impact assessment stage of the standardized LCA methodology, only classification and characterization stages were undertaken here (ISO 14040 2006). Normalization and weighting were not conducted as these optional (and, to some extent, subjective) elements were not considered to provide additional robust information for the objectives established in this study. The characterization factors reported by the Centre of Environmental Science of Leiden University (CML 2001 method) were used (Guinée et al. 2001). The impact potentials (or impact categories) evaluated according to the CML method were: abiotic depletion (ADP), acidification (AP), eutrophication (EP), global warming (GWP), land competition (LC), ozone layer depletion (ODP), and photochemical oxidants formation (POFP). Concerning the GWP, the CML 2001 method excludes biogenic $CO_2$ when computing this impact, so the characterization factors associated have been modified (−1 for uptake and +1 for release) in order to include it and make the obtained results comparable to the available literature. Furthermore, an energy analysis was carried out based on the cumulative nonrenewable fossil and nuclear energy demand (non-ren CED) computed according to Hischier et al. (2009) as an additional indicator. The software SimaPro 7.3 was used for the computational implementation of the inventories (Goedkoop et al. 2008).

### 4.1 Characterization results

The allocated results to biodiesel (i.e., 98 % of the total burdens) for the characterization step are shown in Table 4 for the complete production process (cradle-to-gate perspective). A breakdown of the contribution of the different subsystems involved in the system is depicted in Fig. 2 in order to identify the most contributing subsystem to the selected environmental impact categories.

According to Fig. 2, the SS1, which involves the agricultural activities related to the production of the rapeseed as well as the conversion of the seed into crude oil, was the main hot spot in all the impact categories under assessment, with contributions to the environmental profile between 68 and 100 % depending on the category. Concerning GWP, this subsystem presents a positive environmental performance due to the $CO_2$ uptake during the rapeseed growth, which offsets the 76 % of the GHG emitted throughout the production of the biodiesel (SS1 + SS2). The production of rapeseed oil-derived biodiesel releases ~3.2 t $CO_2$ per ton of biodiesel, ~2.5 t $CO_2$ being derived from the SS1-related activities. The removal of $CO_2$ from the atmosphere by the crop offsets ~2.9 t $CO_2$ resulting on the emission of 109 kg $CO_2$ per ton of biodiesel (see Table 4). The relevance of considering the consumption of biogenic $CO_2$ by the biomass during its growth has already been taken into account in related biofuel production papers (Bai et al. 2010; González-García et al. 2009a; 2009b; 2010a; 2010b; 2010c; 2011; Luo et al. 2009a; 2009b; Tan et al. 2008).

It is important to remark here that the biorefinery under study does not produce rapeseed oil, but it imports the oil from Canada to be further converted into biodiesel. Therefore, we have paid more attention on the SS2, which includes all the activities which take place in the biorefinery and where our principal interest is focused on. However, improvement alternatives focused on the raw material used (SS1) will be proposed in the discussion.

The high contribution from SS1 to the environmental profile is due to the agricultural activities associated to the production of the seed. It is important to remark here that information concerning the production of the rapeseed was taken from the Ecoinvent database (Nemecek and Käggi 2007), where rapeseed was cultivated under conventional practices. Therefore, agricultural activities represent 58 % ADP, 80 % AP, 95 % EP, ~100 % LC, 70 % ODP, and 17 % POFP. These results are related to the intensive conditions of the cultivation of the rape, which include the application of fertilizers (NPK-based fertilizers) and pesticides, the diffuse emissions from agrochemical application as well as arable land occupation for rapeseed cultivation (the main source contributing to the LC impact). Diffuse emissions of ammonia to the air and nitrate to the water showed a remarkable contribution to EP. Combustion emissions from agricultural machineries were also taken into account and showed a remarkable contribution to AP, ODP, and GWP. However and as it was mentioned

**Table 4** Impact assessment results (characterization step) associated to the production of 1 t of biodiesel

| Impact category | Unit | Value |
|---|---|---|
| Abiotic depletion (ADP) | kg $Sb_{eq}$ | 13.83 |
| Acidification (AP) | kg $SO_{2eq}$ | 20.07 |
| Eutrophication (EP) | kg $PO_4{}^{-3}{}_{eq}$ | 14.00 |
| Global warming (GWP) | kg $CO_{2eq}$ | 109.31 |
| Land competition (LC) | $m^2a$ | 5,275 |
| Ozone layer depletion (ODP) | kg CFC-$11_{eq}$ | $2.06 \cdot 10^{-4}$ |
| Photochemical Oxidants Formation (POFP) | kg $C_2H_{4eq}$ | 1.43 |
| Cumulative nonrenewable energy demand (non-ren CED) | $GJ_{eq}$ | 34.32 |

before, the role of biomass in removing $CO_2$ from the atmosphere gives a favorable result in terms of GWP.

Concerning SS2, Fig. 3 shows the relative contributions of each of the seven considered life cycle sections in every impact category. Accordingly, the pretreatment (SS2.2) and transesterification (SS2.3) sections were the most important contributors to all the impact categories under assessment with percentages higher than 68 % and even up to 77 % for ODP. They were followed by far for the ancillary activities section (SS2.6) which showed contributions up to 17 % in GWP. It is important to point out that this section includes the production of heat requirements in the biorefinery and natural gas is used as feed in the boilers. Although the contributing processes to each category will be discussed later per impact category and section, we would like to remark here that all the electricity requirements are satisfied with electricity taken from the Spanish national grid, which considerably depends on fossil fuels. For this reason, this process considerably influences the environmental results. Other potential contributors to the environmental profile were the manufacture and provision of the chemicals consumed in the different stages of the biorefinery. According to the results, improvement alternatives should be focused on the sections previously mentioned.

#### *4.1.1 Abiotic depletion potential (ADP)*

SS2.3 was the main contributor section, with 57 % due to methanol production and distribution (71 % SS2.3). This is followed by SS2.2 (23 %) because of the electricity requirement taken from the national grid (72 %), which considerably depends on fossil fuels.

#### *4.1.2 Acidification potential (AP)*

Both the pretreatment and transesterification sections presented large contributions: 47 % and 22 %, respectively. The main process involved in both results was electricity production (53 % and 58 %, respectively) due to combustion emissions derived from fossil fuels.

#### *4.1.3 Eutrophication potential (EP)*

The 42 % of contributions to EP were due to SS2.2, once again due to the production of the electricity requirements (62 %). This process was also the key factor of contributions from SS2.3 (29 % of total).

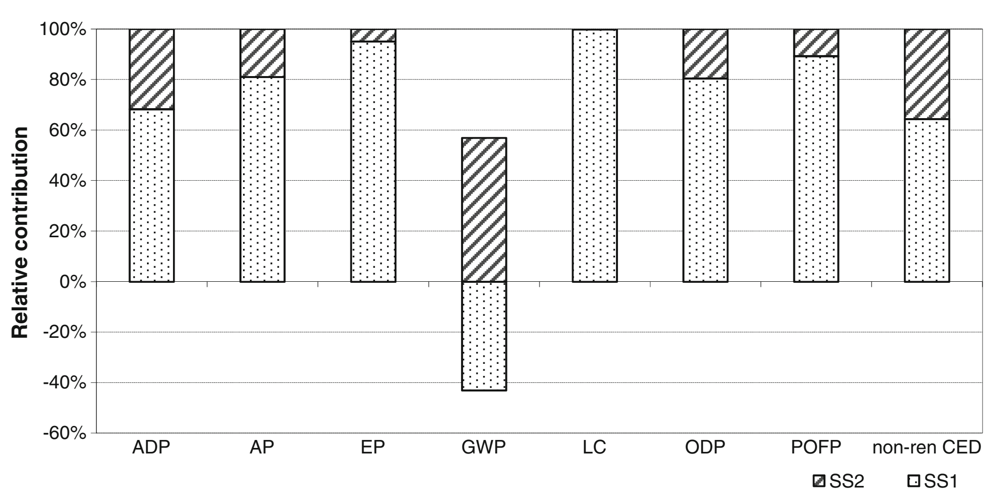


**Fig. 2** Relative contributions per subsystem (in percent) to each impact category. Impact categories: *ADP* abiotic depletion, *AP* acidification, *EP* eutrophication, *GWP* global warming, *LC* land competition, *ODP* ozone layer depletion, *POFP* photooxidant formation, and *non-ren CED* cumulative nonrenewable energy demand. Subsystems: *SS1* rapeseed oil production, *SS2* biodiesel production

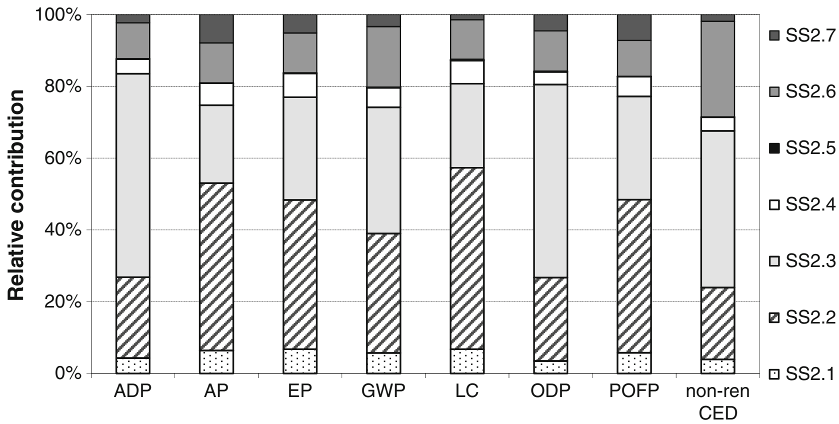


**Fig. 3** Relative contributions per section of the biorefinery subsystem (SS2) to each impact category (in percent). Impact categories: *ADP* abiotic depletion, *AP* acidification, *EP* eutrophication, *GWP* global warming, *LC* land competition, *ODP* ozone layer depletion, *POFP* photooxidant formation, and *non-ren CED* cumulative nonrenewable energy demand. Sections: *SS2.1* storage tanks of chemicals, product, and coproducts, *SS2.2* pretreatment, *SS2.3* transesterification, *SS2.4* WWTP, *SS2.5* lab activities, *SS2.6* ancillary activities, *SS2.7* distribution

### *4.1.4 Global warming potential (GWP)*

The transesterification section showed the highest contribution to the GHG emissions (35 %) specifically due to electricity requirement production, potassium methylate production and chemical transport (mainly methanol and potassium methylate). It was followed by the pretreatment section (33 %) where the production of electricity requirement was again the hot spot. It is important to point out the contributions to this category from diffuse emissions (specifically $CO_2$) from SS2.2 and SS2.6 which represented the 10 % of GHG derived from the biorefinery activities.

### *4.1.5 Land competition (LC)*

In this category, land occupation it is taken into account. Therefore, the pretreatment section was the main hot spot (51 %) followed by the transesterification section (23 %). Silica gel and electricity production considerably influenced the results.

### *4.1.6 Ozone layer depletion potential (ODP)*

The transesterification section (SS2.3) was responsible for 54 % of contributions from SS2 to this impact category mostly due to methanol production (61 % of contributions from this section). It was followed by the pretreatment section (SS2.2) with a remarkable contribution of 23 % because of electricity requirement in this section.

### *4.1.7 Photochemical oxidant formation potential (POFP)*

The 43 % of contributions to this category are due to SS2.2 and is followed by SS2.3 (29 %). Electricity and chemical production were responsible for both results.

### *4.1.8 Cumulative nonrenewable energy demand (CED non-ren)*

The highest energy demand corresponded to SS2.3 (44 %) followed by SS2.6 (27 %) and SS2.2 (20 %). These results are due to the production of electricity requirements (the main key issue), since it is taken from the national grid which mainly depends on fossil fuels, production of chemicals (mostly methanol), and natural gas required in the boilers.

## 5 Discussion

The production of biodiesel has been studied in the literature from an environmental and energy points of view using different raw materials for its production: cooking oil (Talens Peiró et al. 2010), rapeseed oil (Talens Peiró et al. 2010; Mata et al. 2011), soybean oil (Panichelli et al. 2009; Mata et al. 2011), palm oil (Mata et al. 2011), jatropha oil (Mata et al. 2011), sunflower oil (Mata et al. 2011) as well as algae (Sander and Murthy 2010; Mata et al. 2011: Shirvani et al. 2011). The interest on this biofuel is in the political and economic arenas and only in 2007, 19 biodiesel plants in the new European member states started to operate or were under construction (Luque et al. 2008). Special attention is being paid nowadays on the biodiesel from algae due to its numerous advantages: (i) they can accumulate high lipid/starch content, (ii) they have shorter growth cycles as compared to other terrestrial plants, (iii) they can be grown in wastewater unfit for crop irrigation or municipal use, and (iv) they present versatility to grow in diverse climatic conditions and wastewaters (Sander and Murthy 2010; Shirvani et al. 2011). However, this technology is still under development and it is not applied at an industrial scale

(Sander and Murthy 2010). The present study was focused on rapeseed oil-derived biodiesel for several reasons mentioned before, but also because this technology is currently used at an industrial scale and improvement alternatives could be proposed in order reduce the overall energy use and improve the environmental impacts associated. This process is interesting because not only is biodiesel produced but other added value coproducts such as glycerine and gums are also produced. Glycerine is the main coproduct and it has a wide range of applications in the food industry, nitroglycerine, foams, medicines and personal care products manufacture. However, it is produced in low ratios with respect to biodiesel and its economic value is really lower than biodiesel (Luque et al. 2010). In this study, we have included, within the system boundaries, the glycerine stream purification step (in SS2.3) which contributes with extra environmental impacts to the global assessment. An interesting alternative could be the use of this stream for heat production in the biodiesel production system, since biodiesel development has created an excess in glycerine supply resulting in price collapse (Mata et al. 2011).

The interest on biodiesel mainly lies on guaranteeing petroleum-derived diesel demand and supply for future generations (Gomes and Muylaert de Araújo 2009; Mata et al. 2011). For this reason, it is so important to compare the potential benefits of biofuels (i.e., biodiesel) from an environmental perspective in comparison with conventional fuels. LCA can provide a wide set of indicators, and energy as well as global warming parameters are the most common criteria evaluated when forecasting the most convenient energy systems (Yee et al. 2009; García et al. 2011).

In the previous section, the environmental hot spots or key issues all over the life cycle (cradle-to-gate perspective) of the biodiesel system under assessment were identified in different environmental impact categories. According to these results (see Fig. 2), the subsystem related with the crude rapeseed-based oil (main raw material) production (SS1) showed the highest contribution to all the assessed categories specifically due to the agricultural activities focused on the rapeseed crop. This result fits in with Panichelli et al. (2009) and Mata et al. (2011) where soybean-, rapeseed-, and palm oil-derived biodiesel productions were analyzed from a LCA approach. According to these studies, the impact of biodiesel production is highly dominated by the agricultural phase in all the impact categories under assessment.

### 5.1 Sensitivity assessment of rapeseed oil origin

Concerning the raw material, unrefined rapeseed oil is used in biodiesel refinery under study as main raw material to produce biodiesel. As mentioned before, rapeseed is one of the main feedstocks used for European biodiesel production, and Europe is also the biggest producer (Stromberg et al. 2010). However, all rapeseed oil consumed by the biorefinery is supplied from Canada instead of from Europe due to economic reasons (i.e., lower sales price). The environmental burdens associated to rapeseed oil transportation (maritime transport) are really low (less than 3.5 % to all impact categories assessed), since the highest contribution comes from the agricultural process as it was previously shown. However, the promotion of local or regional feedstocks specifically, in the case of rapeseed in Europe is interesting. Therefore, a sensitivity assessment was performed by assuming differences not only on the rapeseed production between countries but also on the distance and mode of transport. For the former, four alternative scenarios have been defined for the agricultural stage: conventional cultivation in Saxony-Anhalt region in Germany, conventional cultivation in Barrois region in France, and integrated production as well as organic cultivation in Switzerland (all dataset from Nemecek and Käggi 2007). For the latter, average distance from the main rapeseed production regions to the biorefiney (Eurostat 2011) were taken: 2,657 km from Germany, 1,369 km from France, and

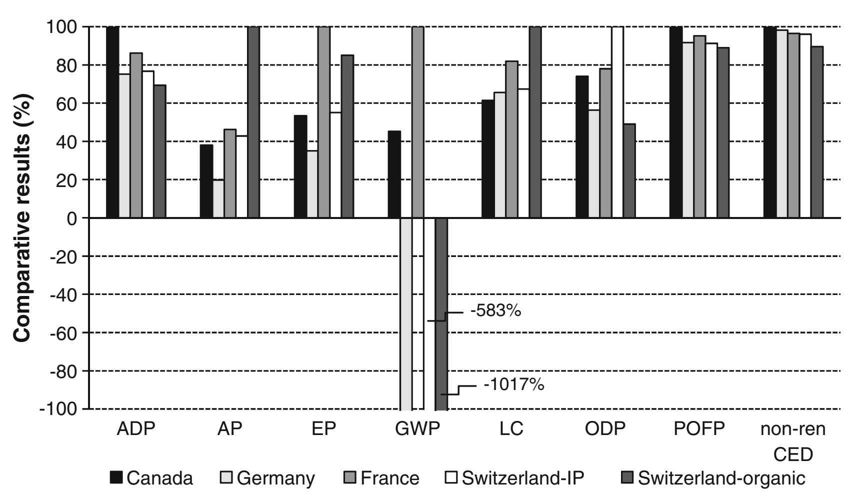


**Fig. 4** Comparative global environmental impacts for rapeseed from Canada, Germany, France, and Switzerland under different crop management. Impact categories: *ADP* abiotic depletion, *AP* acidification, *EP* eutrophication, *GWP* global warming, *LC* land competition, *ODP* ozone layer depletion, *POFP* photooxidant formation, and *non-ren CED* cumulative nonrenewable energy demand

1,997 km from Switzerland, and assumed in all the cases being covered by trucks.

According to the sensitivity results shown in Fig. 4, there are environmental improvements when shifting to European rapeseed suppliers whose distribution is by road and considering different cultivation managements. Depending on the categories and the precedence, the results could change considerably as well as the biomass yield (Nemecek and Käggi 2007). High reductions were achieved mainly in categories, such as, ADP and GWP, and especially when rapeseed is cultivated in Switzerland under organic management. On the contrary, this cultivation process showed the worst results in terms of AP and LC due to the low yield in comparison with the other ones (up to 42 % lower in comparison with German conditions). French rapeseed showed the worst result in EP due to a large amount of nitrate leaching derived from nitrogen-based fertilizer application and in GWP because of the low yield (and lower $CO_2$ uptake associated). Concerning the non-ren CED, it is possible to reduce energy demand but lightly. The highest reduction (10 %) was showed under organic management in Switzerland. The results of non-ren CED are considerably influenced not only by the agricultural stage but also because fossil fuel requirement per kilometer is lower for maritime transport.

### 5.2 Energy balance

In order to clarify the energy performance of the biodiesel production system under assessment, its corresponding energy balance has to be computed. Based on the lower heating value of the biodiesel product,[1] the biofuel scenario potentially produces 37.53 GJ per functional unit (i.e., 1 t of biofuel) that is the direct energy stored in the biofuel. The total energy consumption derived from nonrenewable primary energy sources (non-ren CED indicator) for all the cycle (SS1 and SS2) has been estimated at 34.32 GJ per ton of biodiesel (see Table 4). This positive balance should indicate that the biodiesel scenario is feasible from an energy perspective.

### 5.3 Comparison of rapeseed oil-derived biodiesel with diesel

The replacement of fossil fuels in the transport sector with biomass-based fuels could help to reduce current GHG emission levels and environmental impacts (Luque et al. 2010; Singh Singh et al. 2010). However, regarding liquid biofuels, there are some obstacles and constraints that need to be overcome if biodiesel is regarded as a sustainable and cost-effective energy source.

At present, compared to petroleum-based fuels (i.e., diesel), biofuels are commercially uncompetitive, since the related technology is still under development not only for 2 G/3 G biodiesel but also for bioethanol production processes (Antizar-Ladislao and Turrion-Gomez 2008). Nevertheless, despite current techno-economic limitations, biomass is set to play a role for the achievement of the targets established by the Directive 2009/28/EC on the promotion of the use of energy from renewable sources (Thomas 2011). Within this framework, an environmental comparison between the proposed biodiesel scenario and conventional diesel scenario is presented in this section in order to find an answer to one of the goals of this study: identify the environmental drawbacks and advantages associated with the use of biodiesel instead of petroleum-based diesel in a conventional 28-t truck. To do so, the functional unit assumed was 1 tkm of transported goods. Biodiesel is assumed to completely replace petroleum-derived diesel in the trucks, that is, B100. Fuel economy assumed was 0.27 kg $km^{-1}$ and 0.25 kg $km^{-1}$ for biodiesel and diesel, respectively (Jungbluth et al. 2007; Spielmann et al. 2007). The impact of the use stage was assumed to be the same for all the biodiesel pathways and is directly taken from Ecoinvent database (Jungbluth et al. 2007) as operation of a 28-t truck with 100 % rapeseed oil-derived biodiesel. Operation of a 28-t truck with conventional diesel is also taken from the same database (Spielmann et al. 2007).

The comparative results for all impact categories are shown in Fig. 5, where the production of the fuel, the distribution of fuel from the corresponding refinery to the end user, and the operation of fuel station were considered. The combustion emissions derived from the fuel use in the truck as well as infrastructures and truck construction and maintenance were also included within the system boundaries. According to the results, shifting from conventional diesel to B100 presents a better environmental profile in terms of several categories such as ADP, GWP, ODP, and non-ren CED, while the profile gets worse in the remaining indicators. These results are in line with other related studies where the biofuel and conventional fuel were compared (González-García et al. 2009a; 2009b; 2010a; 2010b; 2010c; Fu et al. 2003; Bai et al., 2010; Canola Council of Canada 2010; Panichelli et al. 2009; Mata et al., 2011). The environmental results depend on several factors such as the selection of the system boundaries, the type of biomass considered, the allocation procedure, or the methodology considered. Differences identified between our results and the study about rapeseed biodiesel production in Canada carried out by the Canola Council of Canada (2010), specifically in terms of GWP where reductions of 90 % were identified shifting from conventional diesel to biodiesel, are

[1] http://www.essom.com/backend/data-file/engineer/engin21_1.pdf [accessed October 10, 2011]

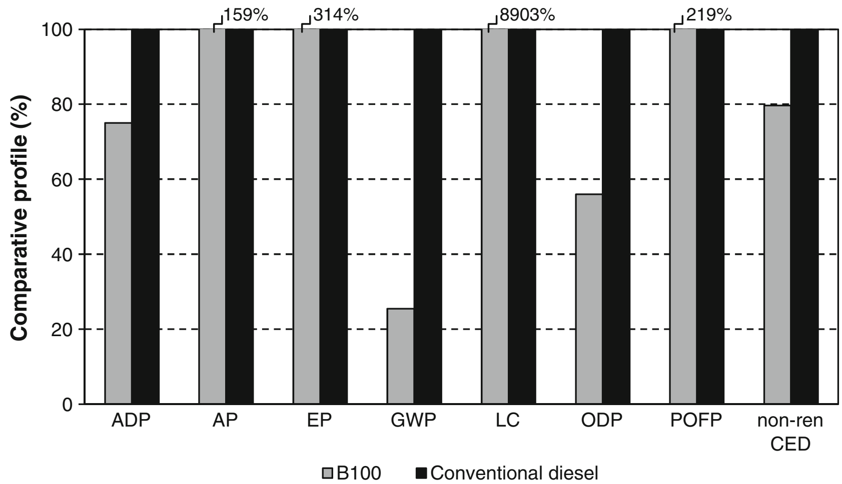


**Fig. 5** Comparative environmental impacts for rapeseed oil-derived biodiesel (B100) and petroleum-derived diesel (conventional diesel) use in a 28 t truck. Impact categories: *ADP* abiotic depletion, *AP* acidification, *EP* eutrophication, *GWP* global warming, *LC* land competition, *ODP* ozone layer depletion, *POFP* photo-oxidant formation, and *non-ren CED* cumulative nonrenewable energy demand

mainly due to these mentioned factors. According to Mata et al. (2011), the use of biodiesel derived from different feedstocks in order to displace the diesel in transportation activities should be an effective strategy for reducing GHG emissions but considering sustainable cultivation management practices and not using land with high carbon stock and high biodiversity areas. On the contrary, biodiesel should present lower energy efficiency due to the higher energy requirements in the related conversion processes in comparison with diesel. However, this last statement depends on the feedstock considered, since some energy crops, if they are cultivated under reduced tillage methods (e.g., soybean), could drive to lower use of fossil fuels in the agricultural phase and more favorable results for non-ren CED instead of diesel (Panichelli et al. 2009). Moreover, a general statement in all the biofuel-related studies (González-García et al. 2009a; 2009b; 2010a; 2010b; 2010c; Fu et al. 2003; Bai et al. 2010; Panichelli et al. 2009; Mata et al. 2011) is that the GWP is lower for biodiesel regardless the feedstock than fossil diesel due to the carbon sequestration in plants during their growth. In addition, tailpipe emissions are lower for biodiesel due to its lower carbon content and in a first approximation, the carbon sequestration could be considered the same as fossil $CO_2$ emissions derived from biodiesel combustion (Panichelli et al. 2009).

Going a bit further, it is important to identify the main differences between the transports using both fuels. Fig. 6a and b shows the distribution of contributions to each category under assessment depending on their origin: fuel (biodiesel or diesel) production including its distribution at fuel station, tailpipe emissions derived from the fuel combustion in the lorry, and finally, contributions from maintenance of lorry and roads derived from its use.

According to the results, in the rapeseed oil-derived biodiesel scenario, the activities related with the production of biodiesel and distribution up to the fuel station are responsible for more than 50 % of contributions to all categories under analysis except for the GWP where the contribution adds to 13 %. These results fit in with

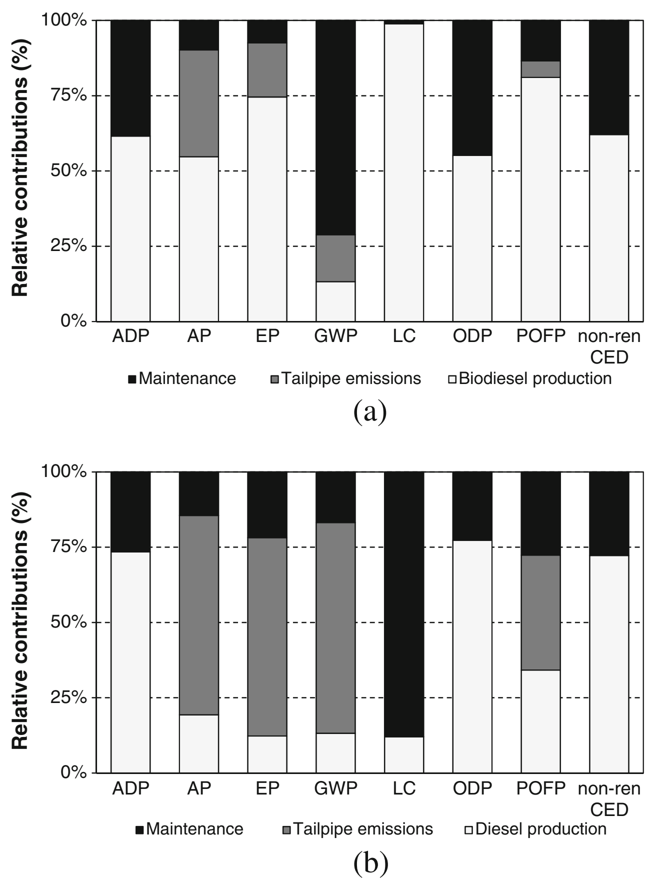


**Fig. 6** Relative contributions (in percent) per stage involved all over the life cycle of the biodiesel B100 (**a**) and conventional diesel (**b**) from a cradle-to-grave perspective to each impact category. Impact categories: *ADP* abiotic depletion, *AP* acidification, *EP* eutrophication, *GWP* **global** warming, *LC* land competition, *ODP* ozone layer depletion, *POFP* photooxidant formation, and *non-ren CED* Ycumulative nonrenewable energy demand

Panichelli et al.'s (2009) where biodiesel production and use was assessed from an LCA perspective and considering different feedstocks. Tailpipe emissions considerably contribute to AP (35 %) and EP (18 %), as Panichelli et al. 2009, due to $NO_x$ emissions. Maintenance role is important in terms of ADP (38 %), GWP (71 %), ODP (45 %), and non-ren CED (38 %) due to the requirement of fossil fuels for the lorry and infrastructures. Concerning the diesel profile, combustions emissions showed the highest contribution to AP, EP, GWP, and POFP (66 %, 66 %, 70 %, and 38 % of total, respectively). The flows of contributing substances to these impact categories are increased up to 15 % in AP and EP, 94 % in GWP and 69 % in POFP, since diesel combustion increases CO and $SO_2$ emissions and $CO_2$ emissions cannot be compensated by the biogenic carbon uptake as in the case of biodiesel. Moreover, tailpipe $CO_2$ emissions per kilogram of biodiesel burnt in the lorry are lower than for conventional diesel, since biodiesel has lower carbon content and it is a naturally oxygenated fuel (Mata et al. 2011). Concerning $NO_x$ emissions, they could lightly be increased up to 10 % (Delucchi 2003).

### 5.4 Influence of the allocation method

Allocation procedure is a critical issue in LCA studies because the environmental results considerably vary according to the allocation factors. Each allocation method (mass, economic, and energy) has advantages and disadvantages and choice of the allocation procedure depends on the limitations of the study. As it was previously specified, economic allocation based on annual sales on the company was assumed. Therefore, 98 % of environmental burdens were allocated to biodiesel, 1.45 % to glycerine, and 0.55 % to gums. However, economic values can fluctuate, since they depend on their availability and need in markets. Thus, they could introduce uncertainty in the results. The results should be lightly different if mass allocation was considered instead of economic allocation. The mass-based allocation factors assigned to the different products should be: 88.5 % for biodiesel, 9.7 % for glycerine, and 1.8 % for gums. Regardless of the partitioning method (Table 5), biodiesel should receive the highest environmental burdens, but reductions around 9.5 % in the environmental flows should be achieved for this product. On the contrary, the environmental results for each impact category should considerably be increased for the reaming products with increments of 667 % and 327 % for glycerine and gums, respectively. Therefore, the choice of the allocation method must be carefully selected, since it can be dangerous for policy decisions.

## 6 Conclusions

This work examines the production of biodiesel derived from the transesterification of rapeseed oil, paying special attention to the environmental profile associated to the manufacture life cycle (cradle-to-gate perspective). This biodiesel production system was selected as it is one of the most important raw material used nowadays not only in Spain but also in Europe. Thanks to the quantity and quality of the inventory data gathered in this study, this work can constitute a baseline to analyze the environmental profile of this interesting biodiesel production process.

The results pointed out the agricultural activities related with the production of the rapeseed as the main key issue in environmental terms mainly because of the fertilizer doses and intensive agricultural practices required. With regard to the biorefinery production process, pretreatment and transesterification sections entailed the highest environmental burdens mostly due to electricity and chemical requirements. The promotion of local crude rapeseed oil (main raw material in the biorefinery), the production of heat from glycerine as well as the substitution of the natural gas in the boilers by a renewable fuel could be interesting improvement alternatives which could help to improve the environmental performance of the process.

The study was complemented with a comparative assessment of biodiesel (B100) and conventional diesel use in a 28-t lorry in order to identify environmental advantages and

**Table 5** LCA results for the different products according to the mass allocation method

| Impact category | Unit | Biodiesel | Glycerine | Gums |
|---|---|---|---|---|
| ADP | kg $Sb_{eq}$ | 12.49 | 1.37 | 0.25 |
| AP | kg $SO_{2eq}$ | 18.12 | 1.99 | 0.37 |
| EP | kg $PO_4^{-3}{}_{eq}$ | 12.64 | 1.39 | 0.26 |
| GWP | kg $CO_{2eq}$ | 98.71 | 10.82 | 2.01 |
| LC | $m^2a$ | 4,764 | 522 | 97 |
| ODP | kg CFC-$11_{eq}$ | $1.86 \cdot 10^{-4}$ | $2.04 \cdot 10^{-5}$ | $3.78 \cdot 10^{-6}$ |
| POFP | kg $C_2H_{4eq}$ | 1.29 | 0.14 | 0.03 |
| Non-ren CED | $GJ_{eq}$ | 30.99 | 3.40 | 0.63 |
| % change relative to economic allocation | | −9.7 % | +667 % | +327 % |

drawbacks of using biodiesel. According to the results, using B100 derived from rapeseed oil instead of petroleum-based diesel would reduce fossil fuel dependence, GHG emissions, and ozone layer depletion but would increase acidification, eutrophication, photochemical smog, and land use. These results fit in with other related studies where not only biodiesel but also bioethanol were considered as transport fuel.

Therefore, it is clear that the widespread implementation of biodiesel (particularly rapeseed oil-derived biodiesel) in our society is enormously complex with many issues involved not only from environmental but also economical and social points of view. Social aspects such as land conflicts, food/feed availability, and effect on prices are associated to this kind of biodiesel. In this context, the 2 G/3 G biodiesel has many chances to become one of the key biodiesel players in the future such as availability feedstock and no competition with feed/food supply although further analysis must be performed in order to be implemented at large scale.

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